A. General Introduction:

The area selected for study is about thirty square miles in extent around Kushalgarh (27°26'N; 76°29'E) and is situated about fifteen miles south-west of Alwar City in Alwar District, Rajasthan (Fig. 1). The area is bounded on the north by the hills of Raikho, on the south by the hills of Seriska Reserve Forest, on the east by the valley of Ruparel and on the west by the alluvial flat ground of Thana Ghazi.

Within the area the Ruparel river flows from west to east along the valley of Kushalgarh; north of Kushalgarh the Ruparel is joined by a tributary river which flows along the valley of Bairawas. The valleys, which contain outcrops of crystalline limestones, calc-silicate rocks, phyllites and mica-schists, are flanked by impressive wall-like ridges of quartzite (Fig. 2). A remarkable feature of the scenery is the absence of outstanding peaks and level summits of the ridges. The ridges are strike ridges and the slopes are dip-slopes of quartzites. Study of topographic maps, aerial photographs and field observations indicate that the persistent narrow width and flat elongate tops of hills are a rule of the topography of the region. The average difference between the level of the Ruparel river valley and that of the summits of surrounding hills is about 400 ft. Rocks are well exposed.
in the valleys and ridges. Only parts of valley areas are covered with soil and these are utilized as agricultural fields by the local populace.

The talc-tremolite rocks around Bairawas are quarried by open-cast method and utilized as 'soapstone' mainly for manufacture of disinfectant. Slabs of crystalline limestones and quartzite are locally used as building materials. Crystals of staurolite and andalusite are abundant in mica-schists near Bairawas and these may be extracted on small scale mining operation.

B. Review of Previous Work :

Northeastern Rajasthan, including the present area, had been geologically mapped and described by Hacket (1877, 1881) and Heron (1917). In the following table the stratigraphic classifications of rocks of northeastern Rajasthan as stated by these authors have been reproduced (cf. Heron, 1917, p. 106).
Table A. Classification of rocks in northeastern Rajasthan.

<table>
<thead>
<tr>
<th>Hacket, 1877</th>
<th>Hacket, 1881</th>
<th>Heron, 1917</th>
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<tbody>
<tr>
<td>Mandan Group</td>
<td>F</td>
<td>Ajabgarh Series F</td>
</tr>
<tr>
<td>Ajabgarh Group</td>
<td>F</td>
<td>D</td>
</tr>
<tr>
<td>Limestone (Kushalgarh)</td>
<td>E</td>
<td>Delhi Series</td>
</tr>
<tr>
<td>Alwar quartzites</td>
<td>D</td>
<td>Alwar quartzite Series</td>
</tr>
<tr>
<td>Alwar Group</td>
<td>Railo limestone and quartzite</td>
<td>C</td>
</tr>
<tr>
<td>Schist Series</td>
<td>A</td>
<td>Aravalli (Undivided) System</td>
</tr>
<tr>
<td>Gneiss</td>
<td>B</td>
<td>Aravalli System</td>
</tr>
<tr>
<td>Gneiss</td>
<td>B</td>
<td>B. Granites intrusive in Aravalli System</td>
</tr>
</tbody>
</table>

According to Hacket (1877) Mandan Group of rocks (slates, schists and quartzites), Ajabgarh Group of rocks (slates, quartzites, breccia, limestone) and Alwar quartzites of Alwar Group occur around Kushalgarh.

The rocks have undergone metamorphism: some of the quartzites are vitreous, the limestones highly crystallized.
and full of minerals like shorl, actinolite, tremolite etc., and the 'schists and slates' highly mineralized containing an abundance of crystals of andalusite, staurolite, garnet etc. Hacket (op. cit.) stated that the rocks in the Alwar territory are folded and repeated many times. He recognized a 'syncline' around Bairawas and a 'dome' around Kushalgarh.

In his second paper (1881) Hacket made a number of changes in stratigraphic classification proposed in 1877. He removed the Ajabgarh and Mandan Groups, and the Raialo rocks from the Upper System ("Aravalli Series" of 1877) and classed these with the Lower System ("Schist Series" of 1877). In other words the Upper System was denuded of everything except the Alwar quartzite which was renamed as "Delhi Series". The name "Aravalli Series" was finally assigned to the rocks of "Schist Series" together with redistributed Mandan, Ajabgarh and Raialo rocks.

In Table A given above the classifications proposed by Hacket (1877, 1881) have been arranged alongside with that proposed by Heron (1917). Heron's (op. cit., p. 105) conclusion on classification of these rocks is as follows — ".... although I strongly disagree with much of Hacket's later work and with the conclusions set forth in his second paper, my survey corroborates almost everything in the first paper".

Heron, who undertook extensive survey of Rajasthan, described the geology in two sectors — North Eastern Rajasthan and Central Rajasthan (Heron, 1917, 1935, 1953; and cf. Gupta,
1934, Pascoe, 1950). In north eastern Rajasthan the 'Delhi System' of rocks are exposed in a belt extending from Delhi southwestwards within latitudes 27°0' - 28°0' N and longitudes 76°0' - 77°0' E. In central and south-western Rajasthan the 'Delhi System' of rocks extend from south of latitude 76°0' N to Palanpur. Regionally the 'Delhi System' of rocks are considered to occur in a 'synclinorium' with an axial trend of NNE - SSW. The present area under investigation occurs in the northern part of north-eastern Rajasthan and structurally forms part of eastern flank of the northern extremity of the 'synclinorium' (Heron, 1917, 1935).

The published geological map of northeastern Rajasthan, which was prepared by Heron (1917, plate 26), is on scale one inch to four miles. The rock types occurring in the Kushalgarh area belong to the stratigraphic units designated as 'Alwar Series', 'Kushalgarh limestone' and 'Ajabgarh Series'. Another unit of rock, termed 'Hornstone Breccia' had been mapped by Heron who explained its status as follows -

"At a varying horizon, sometimes near the base, and sometimes near the top, of the Kushalgarh limestone, comes the hornstone breccia, a rock simulating a bedded deposit but produced probably during the earliest stages of folding by compressive stresses acting on the heterogeneous association of thin quartzites alternating with soft slates, a facies in which compression would produce the maximum..."
shattering with the minimum of folding. There is no evidence that this is of the nature of a thrust fault. The zone of brecciation has subsequently been folded like a bedded rock" (Heron, 1917, pp. 13-14).

The Alwar Series of rocks are mainly quartzites and grits. "In the quartzites, some of which are probably recrystallized quartz grits, quartz, usually in a mosaic of interlocking allotriomorphic crystals without interstitial material, is by far the predominant mineral and normally shows no sign of the original rounded grains, or of secondary growth around them" (Heron, op. cit., p. 30). Ripple-markings and false-bedding are common. "Between the Alwar Series and the Ajabgarh Series and passing conformably down and up respectively into them, through arenaceous and argillaceous transition beds, is the Kushalgarh limestone .... 

........ It is usually conspicuously banded with layers alternating dark grey and black, an inch or two broad, weathering unequally, probably in consequence of the variable proportion of quartzite which they contain .................

......... Besides calcite it usually contains a considerable amount of quartz and some mica and a dusty black substance, probably a form of carbon. It is not dolomitic, where it has been highly metamorphosed, as in the Delawas valley, it loses its banded structure, and amphibole is largely developed in long bladed crystals and in tufts of asbestiform needles ....

......... In the Kushalgarh valley, through which flows the
Ruparel, the limestone has its greatest development and takes its name from here .............. At Kushalgarh the entire floor of the valley is occupied by the outcropping limestone, twisted in various directions" (Heron, op. cit. pp. 56-58). "Above the Kushalgarh limestone and passing conformably down into it, neglecting the occurrence of the hornstone breccia, is the ........ Ajabgarh Series ...........

............. Argillaceous rocks form by far the greater proportion of the series, varying according to their amount of alteration from shales to mica-schists, the commonest degree being that represented by splintery slates with imperfect cleavage, and silvery phyllites. In the latter staurolite, chiastolite and small garnets are locally abundant. As for the remainder, the general nature of the beds may best be described as indefinite, demanding the use of such terms as siliceous limestone, ferruginous quartzite or calcareous slate ............. Speaking generally, the Ajabgarh slates are black or rusty brown, often distinctly banded in differently coloured layers an inch or two thick ...  

............." (Heron, op. cit., pp. 73-74).

Heron (1917, plate 24, figs. 1 & 2) illustrated the structure of the area by means of two sections: one through Talbrich and Alaora (Fig. 3) and another from Tora to Dhamala through Langlheri (Fig. 4) drawn nearly in east-west direction. These show an anticline at Talbrich with Alwar quartzite occupying the core position followed by a
syncline to the east around Langlheri-Bairawas region. The core of this syncline is occupied by the rocks of Ajabgarh Series; these are successively underlain by Kushalgarh limestone and Alwar quartzite. This syncline is followed to the east by an anticline of Alwar quartzite around Raikho. Although no section has been drawn across the hills of Shirunda and Bhadar, and Kushalgarh valley, the complexity of structure had been briefly mentioned by Heron (op. cit., p. 24) as follows - "At Kushalgarh village the Seriska and Bairas synclinal valleys join, bounding with the northern continuation of the Ajabgarh valley, an irregular domed anticline of quartzites".

In recent years Gangopadhyay (1967) made a re-assessment of structural framework of Alwar region within latitudes 27°0' - 28°0' N and longitudes 76°0' - 77°0' E. According to him the major structural pattern of the 'Delhi System' of rocks in Alwar region is dominated by folding on NNE-SSW and NNW-SSE axial trends with general overturning to the easterly direction. Doubly plunging nature, and axial culminations and depressions are notable features of major folding. The style of the major folding may be "disharmonic with polyclinal and box-like shapes particularly in Kushalgarh limestone and Ajabgarh series" (Gangopadhyay, op. cit., p. 424). In the map, showing some "selected structural trends in Alwar region" by Gangopadhyay (op. cit., p. 422), are traces of axial planes of major folds and traces of generalized strike trends. Around Kushalgarh the traces of axial planes are shown to be either
NW-SE or NNE-SSW and a dome-like structure is indicated by strike-trends west of Kushalgarh.

Gangopadhyay and Sen (1968) reported that some open folds, developed on NNW-SSE axes at Kushalgarh and Bairawas, have refolded an earlier set of isoclinal folds.

That the structure of Delhi System of rocks may be complex was hinted at by Heron even in the early stage of investigation in northeastern Rajasthan. Heron (1917, Fig. 4, and plate 24, Fig. 2) did suspect, at least locally, that refolded folds occur on large-scale in Alwar region and he recorded his suspicion in an 'alternative' structural section for an area just north of Bairat which is about 12 miles west of Kushalgarh. Similar observation had been recorded recently by Roy (1963a, 1963b). Roy (op. cit.) compiled a "Tectonic Map of India" in which he classed the Alwar territory as an area of Proterozoic folding under the "structural-metallogenic zone of ancient platform (shield)". He described the Anjari-Dariba-Bairat-Gud Kishoridas-Jodhawas belt of Delhi System as a "highly contorted refolded synformal" structure (Roy, 1963b). This north-south trending belt occurs about eight miles west of the present area under investigation.

Recent investigations in other parts of Rajasthan have indicated that the pre-Cambrians of southwestern and central Rajasthan have undergone repeated phases of folding. Sen and Sengupta (1964) described three sets of superposed folds from
Delhi metasediments near Ajmer-Jaipur region: the first two sets trend nearly co-axially N.N.E. and the third W/WNW-E/ENE. Naha, Chaudhuri and Mukherjee (1966) and Naha, Chaudhuri and Bhattacharya (1966) recorded that the pre-Cambrians ('Raialo Series', 'Aravalli System', Banded Gneissic Complex) of Udaipur territory have suffered two phases of folding; an earlier phase of folding, mainly isoclinal, on WNW-ESE axes and a later phase of relatively open folding with subvertical axial planes striking NNE. Examples of fold interference due to superposed deformations in Central Rajasthan have been recently described by Naha and Chaudhuri (1968).

C. Scope of the Thesis and outline of Results:

The present work is aimed to give an integrated detail of structures developed on all scales (major, minor and microscopic) and of metamorphism within the selected area. Regional investigation of structure, stratigraphy and metamorphism of the 'Delhi System' of rocks is beyond the scope of this work.

The area has been lithologically and structurally mapped on a scale of four inches to one mile. In the field each outcrop has been mapped separately. The maps, which have been reproduced in this thesis, are drift copies of the same. Several outcrops have been mapped on large scale in order to represent critical features of geology.
The main object of the investigation is to elucidate the structural geometry and metamorphism of this area and the topics discussed are -

a) Style and orientation of major folds.
b) Style and orientation of minor folds, linear structures and their relation to major folds.
c) Sequence of development of structures of different generations.
d) Metamorphism of the calcareous, argillaceous and arenaceous sediments and the relation between metamorphism and deformation of rocks.
e) Pattern of lattice orientation of constituent minerals of rocks in order to assess the penetrative nature of movement.

The megascopic and microscopic structural data are described in separate sections in the thesis for the sake of convenience only. The final conclusions are based on the analyses of fabric on all scales as well as on consideration of metamorphic features of rocks.

The author has followed the standard procedure given by Ingerson (in Knopf and Ingerson, 1938, pp. 211-262) and by Turner and Weiss (1963) for measurement, recording and representation of megascopic and microscopic fabric data.

In all the fabric diagrams given in this thesis the data have been plotted on the lower hemisphere of an equal area projection.
Outline of Results:

The study of structures on all scales and of metamorphism of different rock types of Delhi System of the area indicates a sequence of movements which affected these rocks in the extreme northeastern part of 'Delhi Synclinorium'. The constituent rock types of Delhi System here - Alwar Quartzites, Kushalgarh Limestones, Ajabgarh Rocks - have undergone at least three phases of movements. During each phase of movement a set of minor structures has developed. During the second and third stages of movements large scale folds developed with their axes at high angles to one another. Due to interference of the folds, structural basins and domes have formed on megascopic scale in the area. The present distribution of mappable lithological units is mainly controlled by these folds. It is notable that the folds of the first generation are tight, near isoclinal, in shape whereas the folds of the second and third generations are more open and asymmetrical in style with a general easterly sense of overturning. The rock types of this area bear impressions of two phases of metamorphism. The metamorphic history is complex and marked by repeated growth of minerals in relation to deformational episodes. In general it may be suggested that a constructive phase of metamorphism affected the rocks prior to the second phase of deformation. A restricted phase of crystallization occurred concomittantly or post-dating the second phase of deformation.